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CONTINUING STUDIES OF AIR TRAFFIC CONTROL SYSTEMS CAPACITY SUMMARY REPORT, 1970-1971

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16. Abstract

This report informally summarizes the work done by Arthur D. Little, Inc., under the subject contract during the past year, and explains the course which the work is expected to take in the following year. The discussion is organized under four topics: Motivation to study air traffic control system capacity, the role of the contractor, accomplishments in the first two years, and proposed future work. It summarizes work reported in more detail in Report No. FAA-RD-71-36 An Approach to the Establishment of Practical Air Traffic Control Safety Goals; Report No. FAA-RD-71-55, Analytical Tools for the Study of Airport Congestion; Report No. FAA-RD-71-107, Factors Influencing Capacity and Efficiency in Air Traffic Control; and Report No. FAA-RD-71-113, Illustrative Applications of Air Traffic Control System Capacity Study Methods.

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1. INTRODUCTION

This report reviews the work which Arthur D. Little, Inc., has been doing under contract DOT FA70WA-2141 on air traffic control (ATC) system capacity, and explains the course which this work is expected to take next year. The material was originally assembled for a briefing at the FAA on October 7, 1971, for a mixed audience of FAA representatives, contractors, and visitors. Some members of the audience had been steadily following the work of Arthur D. Little, Inc., and were interested in a comprehensive progress report summarizing all that had been accomplished. Others have particular problems related to ATC system capacity, and were interested in an opportunity to apply our work to their problems. Still others were there out of curiosity and for general information, to keep themselves and their agencies well informed about what is going on. The briefing was intended to appeal to all these groups.

The discussion is organized under four topics:

1. Motivation to study ATC system capacity,
2. The role of Arthur D. Little, Inc.,
3. Accomplishments of the first two years of the study, and
4. Proposed future work.

2. MOTIVATION TO STUDY ATC SYSTEM CAPACITY

There are many reasons why we are taking a look at ATC system capacity. First, there are technical and operational factors. Some elements of the present ATC system could not function satisfactorily with substantially more traffic. All predictions forecast growth in air transportation, leading to larger, faster, and more numerous aircraft. New types of aircraft, such as supersonic transports and short- or vertical-take-off-and-landing aircraft, are likely to come into use. New technological options, such as inertial navigation systems, satellite surveillance, and automated data processing are within reach.

Second, there are user group pressures. The operating airlines, both individually and through the Air Transport Association, and general aviation are asking for improved ATC services, and the general public is becoming more aware of the role of air traffic control in the safety and efficiency of air transportation. Payment of user charges reinforces the legitimacy of user group demands.

Third, there are political and administrative demands. We need only mention the CARD Committee, the Brooks Committee, and demands which arise periodically during the budget review cycle.

3. THE ROLE OF ARTHUR D. LITTLE, INC.

The purpose of work being performed by Arthur D. Little, Inc. (ADL) is to develop tools for the Federal Aviation Administration (FAA) to use in planning, decision-making, and evaluation of air traffic control. If this sounds too abstract, consider an example of the sort of question which the FAA must answer several times every year: given two alternatives for improving the performance of air traffic control and an estimate of the cost of each, which will assure better overall air transportation system performance when subjected to the increased traffic projected for the near future?

The initial goals of work being performed by ADL are:

- To define the capacity of an ATC system and its major elements,
- To find quantitative relations between capacity and the overall performance of the air transportation system, and
- To find quantitative relations between capacity and the specifications, operating parameters, and environment of the ATC system.

4. ACCOMPLISHMENT IN THE FIRST TWO YEARS OF THE STUDY

A necessary preliminary is to find out how the FAA operates, to learn the functions which air traffic control fulfills for industry, the public and national defense, and to learn how air traffic control relates to operations. We were in this stage during much of our first year of activity, but now we are in a position to apply what we know about operations research, systems analysis, and other branches of science and technology to air traffic control. What we have accomplished is described below under five principal headings:

1. A concept of capacity,
2. A measure of safety,
3. Some analytical tools based on queueing theory,
4. An analysis of system functions comprising air traffic control and a description of system parameters related to capacity, and
5. Applications to certain current FAA problems.

4.1 A CONCEPT OF CAPACITY

We speak of the "capacity" of a component of the air transportation system, such as a terminal, a runway, or an ATC tower, to mean – in a general way – how much traffic it can handle when fully performing its task. In dealing with methods of increasing this capability under conditions of future rising demand – and by means of expensive equipment – it is important to go beyond this general notion: "capacity" must be defined with such precision that the beneficial effects of the suggested improvements can be measured (or computed).

Military operations under combat conditions have shown that the rate of launching or recovery of aircraft from Air Force runways or from aircraft carriers can exceed the rate for civilian airports. The reason for this increase is the much greater *risk* that is considered acceptable in military operations. This illustrates the first principle in giving any definition of capacity: the degree of acceptable risk must be specified.

During rush hour traffic large air terminals can accept aircraft temporarily at a greater rate than they can permit them to land, provided that there are enough stacking spaces they may be held until the traffic thins out. Conceptually, any number of aircraft could be accepted by increasing the holding space sufficiently. To increase capacity by this means incurs *delays*, which increase with the number of aircraft held. Thus, we have a further illustration of the first principle in the precise definition of capacity: the degree of acceptable delay must be specified.

The same can be said about the whole spectrum of service degradations: cancellations, diversions, passenger comfort, and so on. Uncertainties as well as averages figure in too: an accurately predicted time late may degrade service less than randomly occurring unexpected delays. We can now formulate our first principle: *the degree of acceptable risk, delay, and all other significant service degradations must be specified.*

Suppose, then, that the maximum acceptable risk, delay, and other service degradations are given and we wish to define capacity under these restrictions. A further complication is encountered: the effect of the variation in traffic demand during the course of the day of the requests for landing or for takeoff. Consider, for example, the total number of aircraft that wish to land at an air terminal during a 24-hour day. If they arrive at an even rate (e.g., the same number per quarter hour during the 24), a much greater number could be accommodated than if their arrivals (or requests for arrival) are highly peaked; they cannot all be accommodated without holding delays which exceed the established limits. Thus we are led to the second principle governing any exact definition of capacity: *the ability to handle the demand will depend on the demand profile, i.e., the rate of requests for service and the character of the service requested, plotted as a function of time.*

The third and final principle governing any definition of capacity, if it is to be at the same time precise and realistic, is that *it must be stated in terms of probability parameters (statistical quantities such as means, standard deviations, etc.).* This is because no situation involving the handling of aircraft under "real life" conditions can ever be free from random. It is highly appropriate to try to reduce it as much as possible to regularity; but this very process requires the effects of random on capacity to be understood quantitatively – and we are back to our third principle.

In the light of these principles, two extreme formulations of the concept of capacity are appropriate: (1) a single *number*; and (2) a *transformation* of a demand profile into a service profile:

(1) For a minimum acceptable standard of service, the capacity C is the *maximum mean rate of service* (number of aircraft handled per unit time) that can be rendered when the rate of requests is itself uniform. This notion corresponds to a steady-state condition.

(2) Again given a minimum standard of service, let the demand profile D(t) be given. The system in question will then supply a service at the mean rate of S(t) (aircraft per unit time, plotted against time of day t). Remember that D(t) and S(t) are functions of many variables, although they are very simply described by symbols. The correspondence between the demand D(t) and the service S(t), subject to the constraint that the standard of service is no worse than the allowable minimum standard, symbolically represented by

$$D(t) \longrightarrow S(t),$$
$$(C)$$

describes how the system accomplishes this demanded task. It may be compared to the "transfer function" of an electric input-output system. Moreover, if D(t) is the greatest demand that can be handled at an accepted minimum standard of service, that is, if any proportional increase (replacing D(t) by $(1+h)D(t)$, $h > 0$) will result in a failure to meet the service standard, then D(t) is the capacity of the system. Unfortunately, because D(t) is a function of many variables, many different values of D(t) fulfill this condition. The definition of capacity is not complete until all values of D(t) satisfying the condition have been described. As a matter of expediency, it is often easier simply to describe the transformation in the form $D(t) \rightarrow S(t) = CD(t)$. This then is the precise rendering of the concept of capacity.

Definition (1) is simple and has many uses. It is predicated upon the assumption of a steady state or representing a fluctuating demand by averages – yearly, daily, busy hour, or whatever. Therefore, it may represent departure from reality. For limited parts of the air transportation system, where the auxiliary conditions may be easy to detail, such a definition may be quite appropriate. For example, Blumstein's definition of the saturation landing capacity of a single runway is of this type.

The second definition, involving a multi-parameter transformation, is the only general and precise definition, but it is difficult to use. In the first place, "minimum standard of acceptable performance" must be specified. The specification requires many variables, and some of the variables (for instance, noise) are far removed from the principal area of activity of the ATC service. Also, agreement on service standards is not unanimous, because different interest groups will put different weights on various service degradations. Moreover, attitudes toward acceptability may change. For instance, the proportion of flights cancelled on account of weather which was acceptable in 1960 may be considered unacceptable in 1980, or an amount of environmental noise around an airport which is unacceptable under general conditions may be considered acceptable if the suffering public believes a temporary crisis exists.

A second problem is that the standard of acceptable performance relates to the performance of the air transportation system as a whole, not to the performance of air traffic control alone, or to the performance of one element of the system. For example, in examining the effect of delay, we may distinguish between delays on the ground and delays in the air, for the latter are more costly to the airlines; and we may distinguish between predictable delays and delays which occur unpredictably: the former may be less costly to a passenger. On the other hand, whether a particular delay occurred in departure, en route, or in arrival, or whether it took the form of a slowdown, or diversion en route, or circling in a

holding pattern is relatively unimportant to the overall evaluation. The conversion of a standard of overall system performance into standards for the performance of various subsystems and elements is very difficult. There are many ways to budget a total margin among many contributing factors, but they do not all lead to the same capacity.

Finally, the demand profile is a function of many parameters also, not a single number. Gradual changes, such as progressive changes in the mix of aircraft from small propeller-driven aircraft to large jets, can be accommodated by correspondingly small evolutionary changes in the transfer function C. However, the introduction of VTOL and STOL aircraft, for instance, might require a complete reanalysis.

Defining capacity as a single number is too naive to be useful, and defining capacity in terms of a complete transfer function is too complex to be applicable to anything but philosophical discussion. We believe it will be necessary, in general, to specialize and simplify the general definition for each major application rather than to attempt an exhaustive universal definition.

4.2 A MEASURE OF SAFETY

Peter Drucker has said, "... we mistakingly think that one can live in a riskless universe, that one can somehow deprive human action of risk. To believe that one can be (completely) safe is sheer delusion. The real challenge ... is to think through what risks to afford and what risks are not permissible and where to draw the line, and what price to pay for what degrees of insurance ... the moment you want to be riskless, you are ... vulnerable to the wrong catastrophes."

It is interesting that Drucker's statement (from a paper "Why We Are Not Making Much Progress") concerned preserving the environment, but what he says is equally true of air traffic control. One of the impediments to a rational discussion of safety has been lack of a measure which can be applied equally well to air transportation and to other human activities. We have found a new measure of safety in the literature[1] and applied it to air traffic control. Starr introduces the ratio fatalities per hour of exposure, and shows why it is a useful unit. In studying air traffic control, this unit has a number of advantages.

The first advantage of fatalities per hour of exposure as a unit for the measurement of safety is that it makes air transportation risks easy to compare with other risks. The problem in defining the measure of risk is to find the right normalization factor. Everybody understands what a fatality is, but with different normalization factors we can generate fatalities per passenger mile, fatalities per hundred million population, fatalities per million take-offs, and a number of different units. Time is an advantageous normalizaton factor because the flow of time is an experience common to all human beings. The time spent in any human activity can be measured, and serves as a common denominator for comparing risks.

In particular, when risk is measured in terms of fatalities per hour of exposure, man-made risks can be compared with the risk of death from natural causes. As Starr shows, the risk of contracting a fatal disease and dying from it is around 1 in a 1,000,000, ranging from 1 in 10,000,000 for healthy young people to 1 in a 100,000 and more for the elderly. A corollary of this is that risk as small as 1 fatality per 10,000,000 hours of exposure cannot change the life expectancy pattern of a large group of people very much. At this level, the risk of death from a cause other than disease is extremely small. Further reduction of a man-made risk below the level of 1 per 10,000,000 hours of exposure simply serves to decrease the already small probability that death will occur by other than natural causes, without having an appreciable effect on the total fatality rate.

Is it true that a risk smaller than 1 fatality per 10,000,000 hours of exposure is small in a social sense as well as in an actuarial sense? Starr's evidence shows relations between the amount of risk (measured in these units) and the proportion of a population which is willing to participate in the risk-producing activity, and between the amount of risk and the amount of benefit which people expect to receive from partaking of the risk-producing activity. For voluntary risks – activities where people have a real choice about whether to expose themselves to risk or not – when the risk level is well below 1 per 1,000,000 hours of exposure, a very large proportion of the population is willing to expose itself for a small perceived gain. At levels around 1 in 1,000,000, a small proportion of the population exposes itself in sporting activities, such as hunting, for a modest perceived gain, and most people in this country expose themselves to riding in automobiles at this risk level for a large perceived gain, even though the absolute dealth toll from automobile traffic fatalities is around 50,000 per year for the whole country. Any risk which is substantially higher than 1 per 1,000,000 hours of exposure, such as the risk of non-professional general aviation, is likely to be considered dangerous, with limited participation even when the perceived gain may be high. In these terms, therefore, this measure of safety is a useful and convenient medium for discussing acceptability and unacceptability.

As long as the design requirement is *no risk*, many trades and optimizations which ought to be carried out are eliminated completely. For example, we know that exposure to near misses increases with terminal air congestion,[2] and we infer therefore, that the risk of mid-air collision in a terminal area increases as the amount of traffic in the air increases. Part of the terminal-area traffic results from queueing for landing, and is therefore influenced by runway acceptance rate of the terminal. The in-air queue could be decreased by decreasing the minimum separation standard in the final glide path. However, such an action would probably increase the landing risk. It is reasonable to ask the question: What landing procedure minimizes the joint risk of terminal area mid-air collision and final landing? To the best of my knowledge, this question has never been examined quantitatively. It is extremely difficult to examine until a unit of safety has been adopted, and until we understand the usefulness of deliberately increasing the risk in one part of the system in order to achieve an even greater reduction in risk in another part.

Another advantage of this measure of safety is its usefulness in establishing practical safety goals. This is discussed at length in another report.[3] Some of these ideas have already been used by Mr. Braverman of NAFEC.[4]

Although the concept of an acceptable risk is repugnant to many, we will show a little bit of evidence that an acceptable risk level is already achieved. Figure 4.1 (reproduced from one of our recent reports[5]) shows the number of fatal accidents versus regular hours flown for U.S.-certified air carriers in scheduled passenger service for the 12 years from 1956 through 1967. These points are plotted on a special paper with a rather particular set of coordinate axes.[6] A distinctive property of the paper is that, for binomial and Poisson distributions, a dispersion of one standard deviation has the same physical dimension on any part of the coordinate paper. Therefore, deviations from a constant mean rate of plus or minus one or two standard deviations, are represented schematically by a family of parallel lines, as on the figure. If these accidents were all statistically independent, the number experienced in each year would be samples from a Poisson distribution. With 12 sample points plotted on this scale as unit line segments, we could expect approximately 4 to lie entirely outside of the plus or minus one standard deviation limits and would expect, with about 50% probability, that one would lie outside of the plus and minus two standard deviation limits. As a matter of fact, none fall outside of the two standard deviation limits and only one falls outside of the one standard deviation limits.

This suggests that accidents are not statistically independent but that their occurrence is *more regular* than a totally random Poisson series. In lay terms, immediately after an accident has occurred the probability of a second one appears to decrease, but after a while the probability rises again to its former level. The clustering of the points on the figure is not so tight as to be statistically convincing: the probability of this degree of clustering occurring by chance among 12 points is over 5%, and few statisticians would accept the conclusion of this degree of importance even at a 5% confidence level. On the other hand, from the point of view of controlling safety as a parameter, the safety of U.S.-certified air carriers certainly was not "out of control" during this period of time, and a rapid growth of passenger traffic during this period attests to a certain kind of social acceptability of this degree of risk in exchange for the high economic, social, and military value of intercity air passenger transportation.

4.3. SOME ANALYTICAL TOOLS FROM THE THEORY OF QUEUES

Inasmuch as our work on analytical tools has been reported in detail recently,[7] we shall merely summarize it briefly here. Queue theory has been used extensively in the past, but it has been applied to air traffic control chiefly in terms of steady-state queueing analysis or in terms of computer simulation. Neither of these is adequate for analysis of ATC system capacity. Computer simulation without parallel analysis is deficient, because one can never be certain whether a particular computer result is typical or an accidental extreme, and the generation of enough computer results to describe distributions is usually prohibitively expensive.

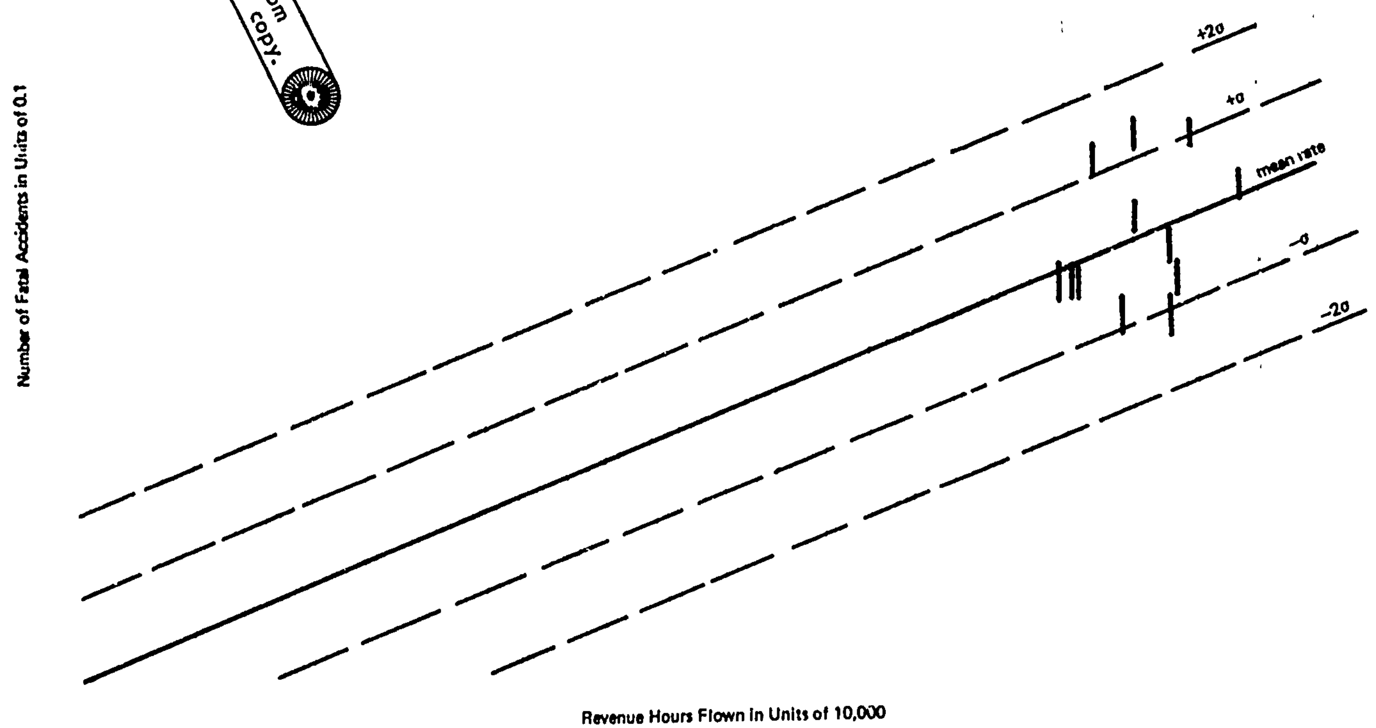

FIGURE 4.1 NUMBER OF FATAL ACCIDENTS VERSUS REVENUE HOURS FLOWN—U.S. CERTIFIED ROUTE AIR CARRIERS, SCHEDULED PASSENGER TRAFFIC, 1956-1967

Steady-state analysis is inadequate because of the importance of dynamic and transients in ATC problems. Both the demand for service and the rate at which the service can be rendered fluctuates with time. If these fluctuations were very slow compared with transit times and queue delay times in the system, we could represent the system at only one moment as being nearly in its steady state and use steady-state statistics. Or conversely, if the fluctuations were extremely rapid when compared with both queue delay and transit times, then one could average the demand and service fluctuations to generate queue statistics based on average demands and service rates. However, the typical time over which demand and service rates fluctuate is neither very much larger nor very much smaller than the typical transit times and delay times: queue delay times may run from a fraction of a minute to an hour or more; transit times may run from 20 minutes to several hours; rush hour peak loads can build up from a very lightly loaded prepeak state to a peak overload within 30 minutes; and a weather change may cause an abrupt change in the service rate of a sector or a terminal within a few minutes. In fact, the dynamics of the building up and decay of queues are much more important in ATC system capacity analysis than any steady-state values.

One of the first important theoretical facts we proved is the existence of a unique periodic solution whenever demand and service rate functions are periodic. Although often assumed, this should not have been accepted without proof. The differential equations of an electrical network superficially resemble those which describe multiple queues. Periodic variation of the coefficients of an electrical network can produce modulators and parametric amplifiers which exhibit unstable and nondeterministic behavior. The constraints and boundary conditions on queues prevent that kind of instability. This means, for example, that a 24-hour periodic set of demand and service conditions can be used as a realistic example of a non-time invariant problem with unique stable solutions.

We have also shown that many important queue parameters are insensitive to service statistics. We developed some numerical examples of a single-server queue based on the demand function shown by the darker line on Figure 4.2.* This curve represents the average combined demand for landings and take-offs at LaGuardia Terminal for one month in 1968, and it is therefore representative of a kind of demand variation which actually exists in the air transportation system. Figures 4.3 and 4.4 show a number of computed queue parameters based on a single-server queue with a service rate of 55 per hour. The significant curves are those represented by solid lines, labelled "constant service time," and dash lines, labelled "random (Poisson) service rate, $\mu=1/c$." This significance is as follows:

In every instance we assumed that the demand is a random Poisson series, the mean parameter of which is represented by the time-varying curve on Figure 4.2. "Constant service

* This and the next two figures are figures 4-1, 4-10, and 4-11, respectively of report FAA-RD-71-55 (Ref. 7).

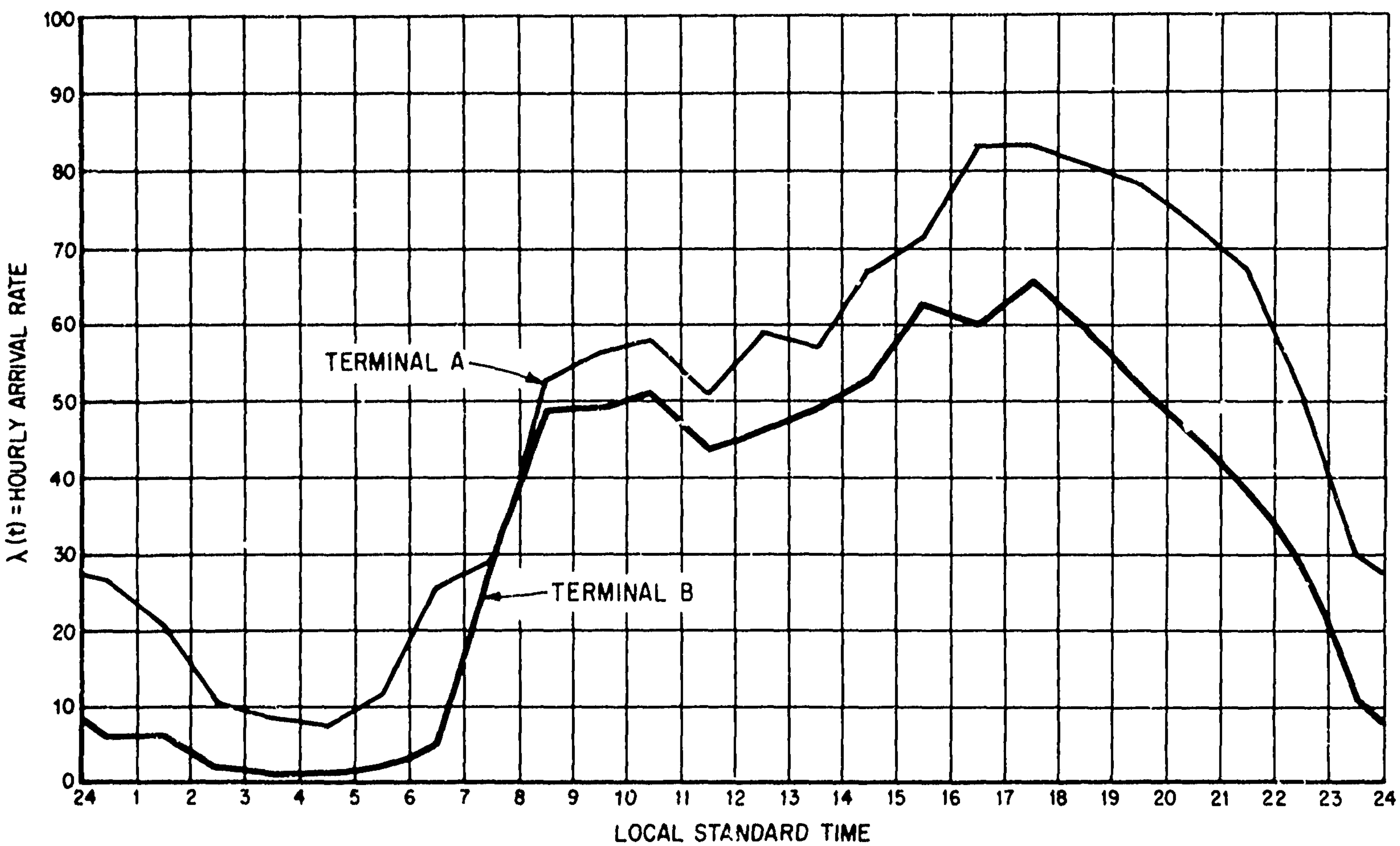

FIGURE 4.2 HOURLY ARRIVAL RATES – TERMINALS A AND B

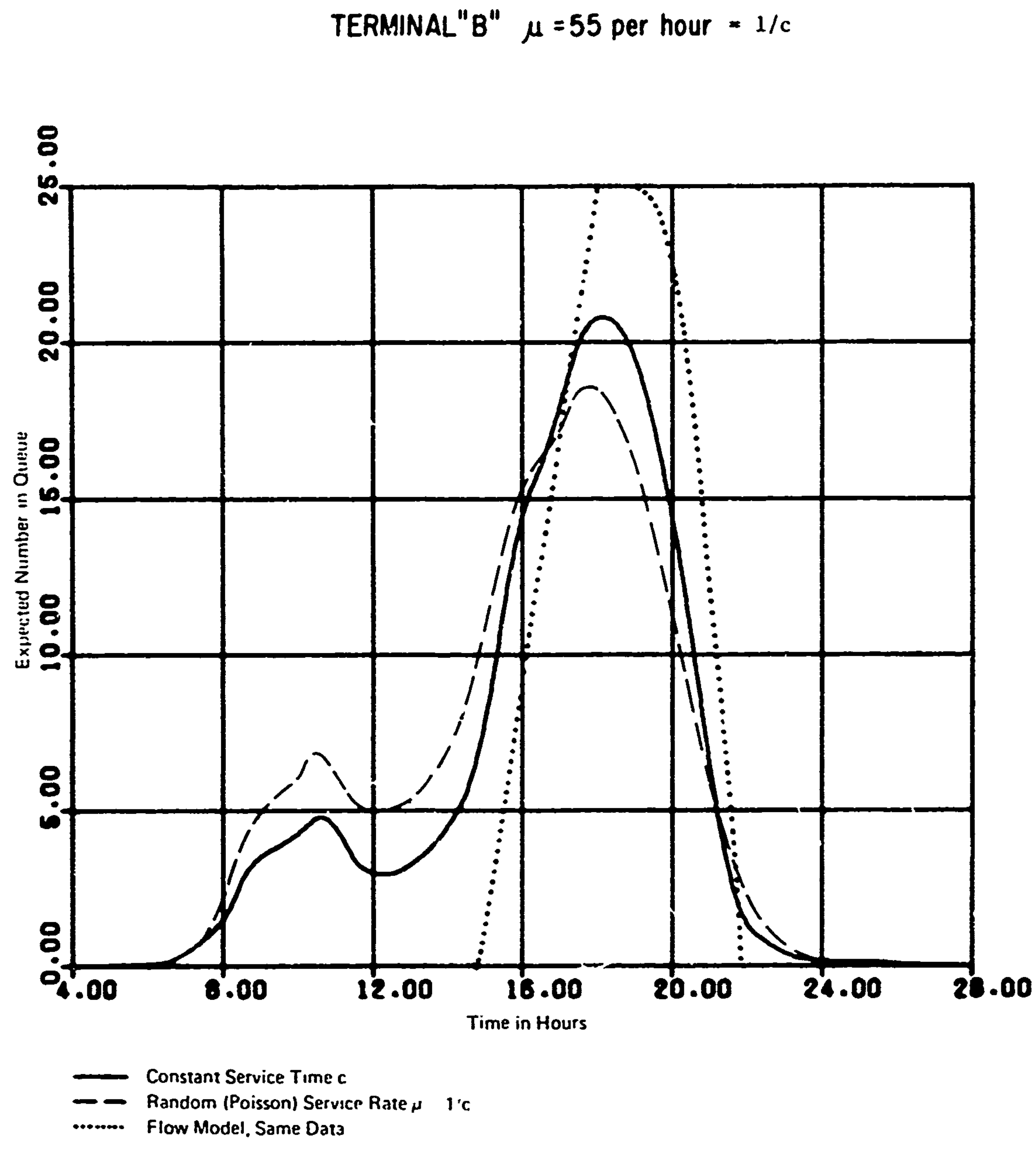

FIGURE 4.3 QUEUE STATISTICS UNDER VARIOUS SERVER ASSUMPTIONS–EXPECTED NUMBER IN QUEUE

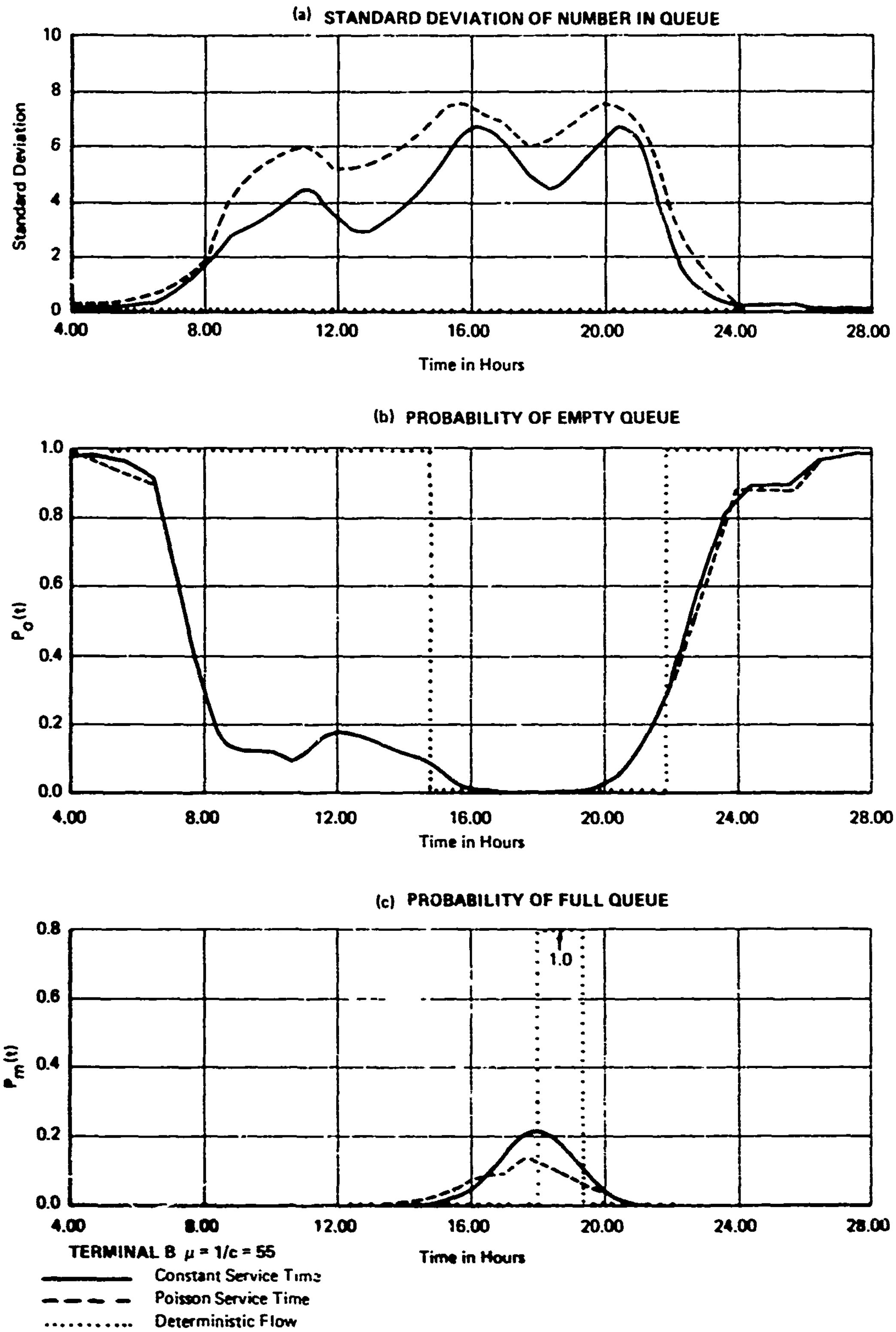

FIGURE 4.4 QUEUE STATISTICS UNDER VARIOUS SERVER ASSUMPTIONS– STANDARD DEVIATION OF NUMBER IN QUEUE, PROBABILITY OF EMPTY QUEUE, AND PROBABILITY OF FULL QUEUE.

time" means that each unit served occupied the system for exactly the same time, 1/55 of an hour or 65.45 seconds, no more and no less. This is an extreme assumption about service time, more regular than can ever occur in real life. "Random (Poisson) service rate, $\mu=1/c$" means that the service times were drawn from an exponential distribution with a mean value of 65.45 seconds. Such a distribution is actually the most random distribution consistent with having a mean value, and service times of all durations from 0 to many times 65.45 seconds occur with substantial probability. This is much more non-uniform than any real terminal area service time distribution could become.

The significance of these computations is that the solid curve and the dashed curve are not very much separated on these four charts. In fact the expected number in the queue (which is very closely related to the waiting time), the standard deviation of the number in the queue, the probability that the queue is empty and the probability that the queue is full differ very little under the two assumptions. Comparing the expected number in the queue with the standard deviation of the number in the queue (Figures 4.3 and 4.4), one can easily see that the difference between the expected values under the two service time assumptions is considerably smaller than the standard deviation of either one. Therefore, if a field experiment or a computer simulation were carried out, one would expect the random fluctuations to be considerably greater than the difference between the curves resulting from the two assumptions.

A practical consequence of this discovery is that we can choose the mathematical representation of server behavior in a way which is computationally convenient, rather than trying to represent realism in this detail of model behavior. For some purposes, the Poisson service assumption is extremely tractable mathematically, but others may be favored in other circumstances.

We have also begun to apply ensemble statistics and perturbation methods to multiple-queue situations. In a queueing model an interconnected complex of runways, arrival and departure zones, and en route sectors involves a large number of queues, each one of which feeds and is fed by others. A complete description of the state of the system would require a description of the state of each queue, and the total number of states is the product of the maximum queue lengths of all the queues in the system. This number of joint states is very large, and to base an analysis or computation on such a model is probably uneconomical, even if it were possible. On the other hand, in many problems in mathematical physics, weakly coupled systems have been handled by writing the differential equations of each subsystem (in our case, each individual queue) in detail, and describing their interactions by letting the coefficients of each differential equation be functions of average behavior of all of the other queues. We are working out a simple example involving two queues, and simultaneously comparing the efficiency of several different computational methods for solving the resulting differential equations in order to find out that which is the most economical. We expect to show very soon that this is a practical, economical, and useful approximation for representing multiple air queues.

4.4 ANALYSIS OF SYSTEM FUNCTIONS AND A DESCRIPTION OF SYSTEM PARAMETERS

4.4.1 Analysis of the ATC System by Functions

We view the ATC system as an information processing (sensing, processing, storage, and display) and decision-making system providing feedback control systems to aircraft and other elements of the whole air transportation system. A year ago we undertook to make a complete description of the ATC system in these terms in order to provide a framework for further quantitative studies. We have identified the gross feedback loops involved in in-air separation (but have never reported this work in formal reports). For the time being we have set this work aside, because we found it more important to list and describe system parameters and operating constraints which appeared to have a direct effect on ATC system or subsystem capacity.

4.4.2 Description of Parameters Relating to Capacity

A report[8] describing a large number of system parameters and operating strengths affecting capacity has been published just recently. This report classifies over 70 types of influence on ATC system capacity and relates them to each other. Certain characteristics and qualities stand out because of their great and intrinsic importance, and numerous relations to other capacity-related characteristics. These are:

- Smaller separation minima, smaller tolerances and margin, higher precision, and rapid responses;
- Controller workload;
- Regularization of flow and responses to peak and statistical fluctuations:
- Interface management; and
- Diversification.

Minima, tolerances, margins, precision, and response time are important because they have a first-order effect on the saturation capacity of a number of subsystems. Controller workload is bound to be an important capacity limitation for economic reasons. Air traffic control is labor-intensive. A very large proportion of the total cost of air traffic control is in controllers' salaries and, therefore, good management of the system requires adaptation of the work pattern so that most controllers are busy most of the time. Flow regularization and response to statistical fluctuations are important because they determine how close to complete the system may be operated before service degradations are unacceptable. Interface management arises in a number of ways, for example, in the proliferation of hand-off

operations required if an attempt is made to increase the system capacity by greatly increasing the number of sectors. Providing alternate functional means of carrying out various functions in the air transportation system has the effect of supplying non-competitive or non-interfering resources which may work together to increase productivity.

These five categories of characteristics and qualities influencing capacity are of primary importance, not only for their first-order effects but because nearly all of the other qualities and characteristics which appear to influence capacity affect one or more of these five categories also.

This work will be set forth in more detail in our forthcoming report.

4.5 APPLICATIONS TO CERTAIN CURRENT FAA PROBLEMS

The purpose of all this work is to provide technical tools which will be useful to people in the FAA responsible for making technical and management plans concerning ATC system capacity. The validity and usefulness of tools under development can only be judged by practical application. Therefore, we are devoting an increasing amount of effort to particular applications of capacity analysis tools. This section is devoted to a review of some of these applications.

We have already alluded to one of our reports, An Approach to the Establishment of Practical Air Traffic Control Safety Goals.[3] The purpose of this report was to demonstrate the utility of the measure of risk described in a previous section by using it as the basis for a method of setting safety goals. This report shows how a knowledge of the incidence of fatal aircraft accidents in the recent past can be combined with an estimate of the overall risk in various types of human activity, which have been found socially acceptable, to produce rational, quantitative goals for the risk associated with air traffic control. Fatal accidents over an 8-year period, from 1961 to 1968 inclusive, are categorized in 36 groups based on 6 phases of flight and 6 type-cause categories. The improvement in overall air transportation safety which could be achieved by reducing or eliminating all sources of accident which are, in any way, related to air traffic control is examined. Inasmuch as the majority of fatalities cannot, by the most generous reckoning, be associated with air traffic control, the total possible improvement is not impressive. When, on the other hand, proportional reduction in risk from all causes is assumed, a set of mutually compatible risk goals for each of the 36 groups can be stated. The report concludes:

(1) The content and quantity of available data are sufficient for this process to be carried out;

(2) The incidence of various classes of accidents is consistent with the use of fatality per hour of exposure as a unit of measurement, and with the assumption of statistical independence among accidents over a moderate period of time;

(3) Passenger and crew risk, in these units, can be reduced to levels characteristic of other human activities perceived as "negligibly risky" only if sources of risk totally outside air traffic control are substantially reduced, as well as risks with a possible relation to air traffic control; and

(4) The number of incidents implied by the resulting safety targets is so small that indirect rather than direct estimation of safety performance would be required to validate any attempts to achieve them.

We have also alluded to the insensitivity of the behavior of certain types of queues to server statistics. The same principles can be applied to analysis of the effects of average service rate, metering, and flow control. Whereas server statistics are of relatively low sensitivity in typical queue formulations, the average service rate is of major importance. Metering affects the statistics of the demand of stream, but not the average rate. Flow control, which may influence time spans longer than those influenced in metering, may affect short-term demand averages, but not the average rate. Flow control, which may influence time spans longer than those influenced in metering, may affect short-term demand averages, but not long-term demand averages. Neither metering nor flow control affects average service rates. We have discussed[7*] a number of implications of these facts. In general, attempts to influence capacity by metering will affect the characteristics of queues operated at air saturation throughput, with delay reductions, but only at the expense of instability. If the demand temporarily exceeds the saturation service rate, the dynamics of queue buildup is relatively unaffected by metering. If flow control can be carried out over a sufficient time span, so that the short-term demand never exceeds the service rate, the full effectiveness of metering and other peak smoothing measures can be reaped. However, this is only a partial solution, for flow control solves the problem only by denying or delaying access to the air transportation system for some users. None of these can be compared in effectiveness with measures which actually increase the saturation throughput, such as making more runways and adding sectors. The latter measures not only increase the saturation productivity, but decrease the sensitivity of the system to perturbations in demand and service level.

In an earlier report[5 **] we referred to the fact that mid-air collisions involving scheduled carrier aircraft are extremely infrequent, so infrequent that the effectiveness of moderate safety improvements cannot practically be estimated from mid-air collision statistics alone. We proposed a model of mid-air collision which could be tested by instrumenting a substantial part of the scheduled air carrier fleet with measurement instruments which would measure distance of closest approach to other aircraft out to a range of 200 yards or

* As well as numerous contacts with FAA personnel.

** See 5.4.

so. The model would be such that if it were validated by experiment, indirect measurement of the risk of mid-air collision could be made with 1000 times less operating experience than required if only actual collisions provided data. This suggestion has never been acted upon by the FAA, probably for practical and economical reasons. It remains as an example of a type of data enrichment, indirect measurements, and non-destructive testing which we believe should be emphasized in the FAA's treatment of safety as a parameter affecting ATC system capacity.

Shortly before the new Chicago Tower was put into use in the summer of 1971, we proposed a method of direct comparison between manual and automated procedures based on the observation that O'Hare airport is normally operated with two independent sets of arrival and departure controllers, with each runway assigned uniquely to one or the other set of controllers. That is, under most conditions the airport is operated as two separate airports which happened to be laid out on the same plot of land. Our proposal was to operate one part manually and the other part with automation, with a balanced experimental design to average out most of the secular variables. Unfortunately, we made this proposal too late to be of any use to the FAA. However, we believe it represents a type of thinking that could be used to advantage later if supported by sufficient advanced planning. This would provide a much more accurate measurement of the effectiveness of terminal automation than any which have been previously attempted.

Last June, the Air Transport Association sent us a brief report on the problem of system-effectiveness measurement. It was prepared by their airline system-effectiveness measurement working group in anticipation of somewhat more formal relationships with the FAA. Since that time, the FAA has responded by designating a group of people to work with the Air Transport Association in resolving some of the issues raised in the ATA memorandum. We have been asked to support the FAA in preparing a position and responding to the real needs of the using public.

The substance of our initial opinion can be summarized as follows. The data requirements for research, development, and investment decisions are determined by the analytical models from which effectiveness is estimated. These analytical models are based upon a detailed understanding of the system and the interaction of its components which consist of both men and machines. Some of the most vital data needed can probably best be obtained by special tests suggested by the analyst rather than by an omni-purpose approach. Such an approach may, however, have value in revealing certain unsuspected factors affecting delay. Suspected factors, such as weather, runway conditions, demand patterns, etc., are already understood, but additional statistics regarding them will be of considerable importance. The ATC system operates as a multiply compensated, highly buffered feedback system in which delay is one of the least costly penalties for system overload. Therefore, delay will be a sensitive index of the degree of loading of the system, but probably a very poor diagnostic index of the cause of the loading.

After a discussion with members of the FAA, we have agreed to do further work to explain the role played by delay in a multiple queueing system, and to explain the distinction between delays which are an accepted or even desired consequence of the successful operation of the control system from delays which can be interpreted as the result of a system fault or inadequacy. This work will probably not be reported in formal reports. It will be effective when it is directly utilized by members of the FAA in a joint approach with the ATA to some of the issues raised in the ATA subcommittee.

5. PROPOSED FUTURE WORK

The general objective of the next phase of our work is to develop a procedure by which the FAA can assess ATC terminal area system performance. This assessment procedure is to be valid for use on the current system to monitor and to detect degradations and their causes. It should also be capable of estimating the impact of proposed future improvements on system performance.

Specifically the effort is to provide a method for:

- Measuring and defining current performances;
- Identifying causal factors of system degradation and the parts of the system which need improvement.
- Providing the method of obtaining the data base needed to assess the benefits of future improvements; and
- Defining the approach to be taken in forecasting the potential benefits of improvements for a busy terminal area.

The context in which this work is to be done is to be a typical major hub, but the results are to be applicable to any other similar area as well.

5.1 APPROACH

We plan to use the Boston Terminal Area for our initial efforts. Starting from an operational description of the area, we will define the principal subsystems involved and, for each of these systems, we will develop measures of performance effectiveness, the operational parameters upon which these measures depend, and the analytical relations between them. On the basis of criteria which reflect relevance, feasibility, etc., we will select performance effectiveness measures which best meet the needs of the FAA. We will also analyze the sources of data to determine which are most suitable as a basis for performance estimation.

5.2 RESULTS

Our principal results in this phase of the work are expected to be as follows:

- A plan for a data collection and analysis program that can be used by the Government for continuous monitoring of a busy terminal area by means of suitably defined system performance measures, and an estimation of the costs for such a system;

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- An evaluation of the role of simulation in contributing to the forecasting of the effects of new equipment or procedures upon the system-performance measures;

- An analysis of the system delay processes to develop the concept of an ATC delay and its elements; and

- Using available data, a demonstration of effects upon the appropriate performance measures of improvements in terminal area equipment or procedures.

REFERENCES

1. Starr, C., Social Benefit versus Technological Risk, Science, Vol. 19, September 1969.

2. Graham, W. H., and Orr, R. H., Terminal Air Traffic Flow and Collision Exposure, Proc. IEEE, Vol. 58, No. 3, March 1970, pp. 328-336.

3. Lister, S. F., and Raisbeck, G., An Approach to the Establishment of Air Traffic Control Safety Goals, Report No. FAA-RD-71-36, Arthur D. Little, Inc., May 1971.

4. Braverman, N., Aviation System Designs for Safety and Efficiency, Navigation, Journal of the U.S. Institute of Navigation, Fall, 1971.

5. Raisbeck, G., Koopman, B. O., Lister, S. F., and Kapadia, A. S., A Study of Air Traffic Control System Capacity, Report FAA-RD-70-70, Arthur D. Little, Inc., October 1970.

6. Mosteller, F., and Tukey, J., The Uses and Usefulness of Binomial Probability Paper, J. Amer. Stat. Assn., Vol. 44, June 1949, pp. 174-212.

7. Koopman, B. O., Analytical Tools for the Study of Airport Congestion, Report No. FAA-RD-71-55, Arthur D. Little, Inc., September 1971.

8. Raisbeck, G., Factors Influencing Capacity and Efficiency in Air Traffic Control, Report FAA-RD-71-107, Arthur D. Little, Inc., November 1971.